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# A STUDY OF FILTRATION THROUGH UNIFORM SAND FILTERS

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SANITARY ENGINEERING DIVISION

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# A STUDY OF FILTRATION THROUGH UNIFORM SAND FILTERS*

Joseph Tso-Ti Ling**

## INTRODUCTION

A number of experiments in rapid sand filtration were carried out during the past years.(1 to 9) In those investigations, only the filter effluent was studied. No facilities were provided for taking samples at different depths of the filter bed. The first test filter used to study the action within the bed was built at the Providence, Rhode Island filtration plant by Eliassen in 1935.(10) An intensive study was made of the time rate of deposit of solid matter in various layers of the filter and the time rate of change of head loss in the filter bed. All tests were restricted to a rapid sand filter with graded sand of fixed effective size and a constant depth of 24". A constant rate of 2 gal./sq. ft./min. was maintained throughout the course of the research.

From the results of the past experiments, it was disclosed that the top few inches of the sand bed accomplished most of the work in a rapid sand filter. The principal functions of the coarser sand and the gravel underneath are to serve as a supporting material for the top layer and to help to evenly distribute the wash water during the back-washing process.

Due to the hydraulic separation of the graded sand bed during back-washing, the top layer of the bed is usually of finer sand, and also the range of variation in sand size is quite narrow in the top when compared to that of the lower portion. In other words, the sand in the top layer which is considered more effective for filtration, tends to be uniform in size. A review of the data of the past experimental work strongly indicated that the results of the tests with sand of uniform size show less variations from the mean value. Armstrong(2,11) pointed out in his report on filter sand, "The greater uniformity of shape of the various curves would indicate that filters composed of sand of a single size would be more dependable than graded sand filters," and also concluded, "If the findings of a limited number of tests can be accepted, an ideal filter should be composed of sand of uniform size." If the above statements are correct, the possibility exists of improving the design of a rapid sand filter with a shallower layer of uniform sand serving as the effective filtering media, supported by some type of bottom structure to replace the coarser sand and gravel, without impairing the quality of the filter effluent.

As Stanley has stated,(11) "It is not unlikely that the present practice might be modified as more definite information becomes available of the effects of various physical characteristics such as size and gradation of filter sand." In the past practice, a graded sand bed is usually considered as a

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combination of a number of very thin layers of uniform sand with various sizes. It is reasonable to believe that the theory of a graded sand filter must be based on that of the uniform sand.

The primary aim of the present research has been a basic investigation of the clarification of water by filtration through uniform sand. Particular attention has been devoted to the basic action of filtration within the filter bed and the effect of sand size, depth of the sand bed, and filtration rate on the removal of turbidity. The change of loss of head during the filter run, the floc storage at successive layers in the bed, and the comparison with the graded sand filter were also studied. It is almost impossible to incorporate all the data and experimental details in this paper, however, they will be presented as briefly as practical without omitting significant observations.

## Description of Experimental Model

The experimental model was arranged similar to a complete small-scale water filtration plant. The model consisted of a rapid-mixing chamber, flocculation basin, sedimentation tank, filters and accessories. The flow diagram of the model is shown on Fig. 1.

In this experiment, raw water of constant turbidity was prepared from Fuller's earth and the tap water of the City of Minneapolis. Electric heating elements were used to heat the city water, when necessary. Constant temperature, 23° c.-24° c., could be maintained in the Raw Water Reservoir by adjusting the temperature of the tap water during the test.

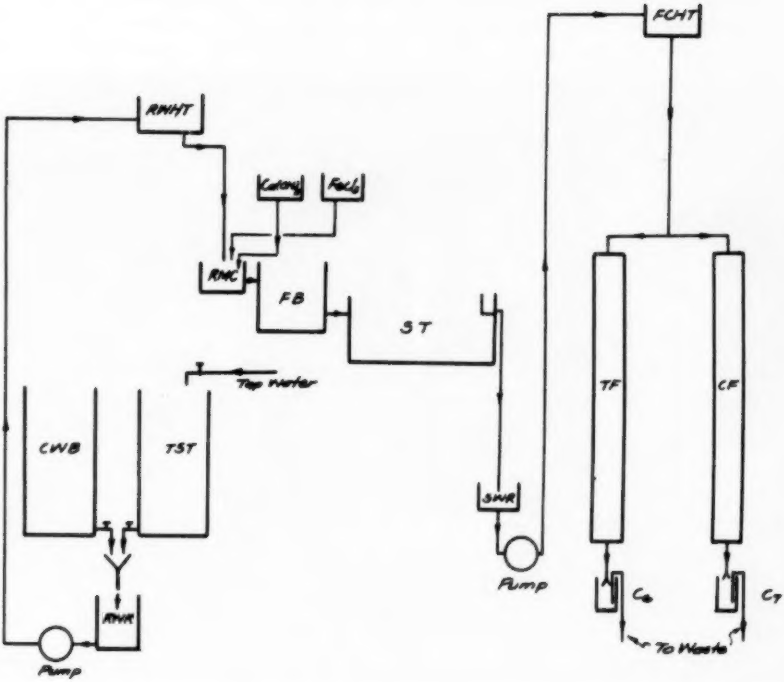
A centrifugal pump was used to raise the raw water from the raw water reservoir to the Raw Water Head Tank. From this head tank, raw water of fixed turbidity 37-38 ppm, flowed at a constant rate to the Rapid Mixing Chamber. Freshly prepared chemical solutions of $FeCl_3$ and $Ca(OH)_2$ were fed continuously to the rapid mixing chamber for coagulation.

A Flocculation Basin equipped with a flocculation paddle was located immediately following the rapid mixing chamber. After the water was flocculated about 20 minutes in the flocculation basin, the flocculated water flowed to the Settling Tank by gravity. A perforated inlet baffle was installed in the settling tank to obtain more uniform distribution of flow. An adjustable V-notch weir was used to collect the effluent uniformly at the outlet end of the tank. The settled effluent was collected in a reservoir from which it was pumped up to the Filter Constant Head Tank. The water then flowed to the Filters.

Two filters were used in this experiment. One of them was a control filter in which graded sand was used, while the other filter was tested with uniform sand. Both filters were identical in construction.

The filter is made of a 4'-4" long plexiglass tube with 2-1/4" inside diameter. (See Fig. 2 for details) Piezometer tubes ($PT_1$) spaced at 3" center-to-center were provided in each filter. One end of each piezometer tube was open at the center of the filter, and a 45-mesh brass screen was mounted in the opening to prevent entrance of sand during sampling. At the other end of each piezometer tube, a short rubber tubing was connected which led to a glass tee ($GT_1$). One leg of the tee was equipped with a pinch-cock and a short piece of tubing from which the samples of water were taken (SP). The other leg was connected to a second tee ($GT_2$) which served as an air blow-off valve.

A third tee ($GT_3$) mounted on the Head Loss Gauge Board (HLGB) was connected to the blow-off valve. One leg of the third tee led to one of the manometer tubes from which the head loss in the filter could be directly read.




**Flow Diagram of Experimental Model**

**Fig. 1**

CWB - Clear Water Barrel
TST - Turbidity Storage Tank
RWR - Raw Water Reservoir
RWHT - Raw Water Head Tank
RMC - Rapid Mixing Chamber
FB - Flocculation Basin
ST - Settling Tank
SWR - Settled Water Reservoir
FCHT - Filter Constant Head Tank
TF - Test Filter(Uniform Sand)
CF - Control Filter(Graded Sand)
$C_6, C_7$ - Filter Effluent Rate of Flow Controller

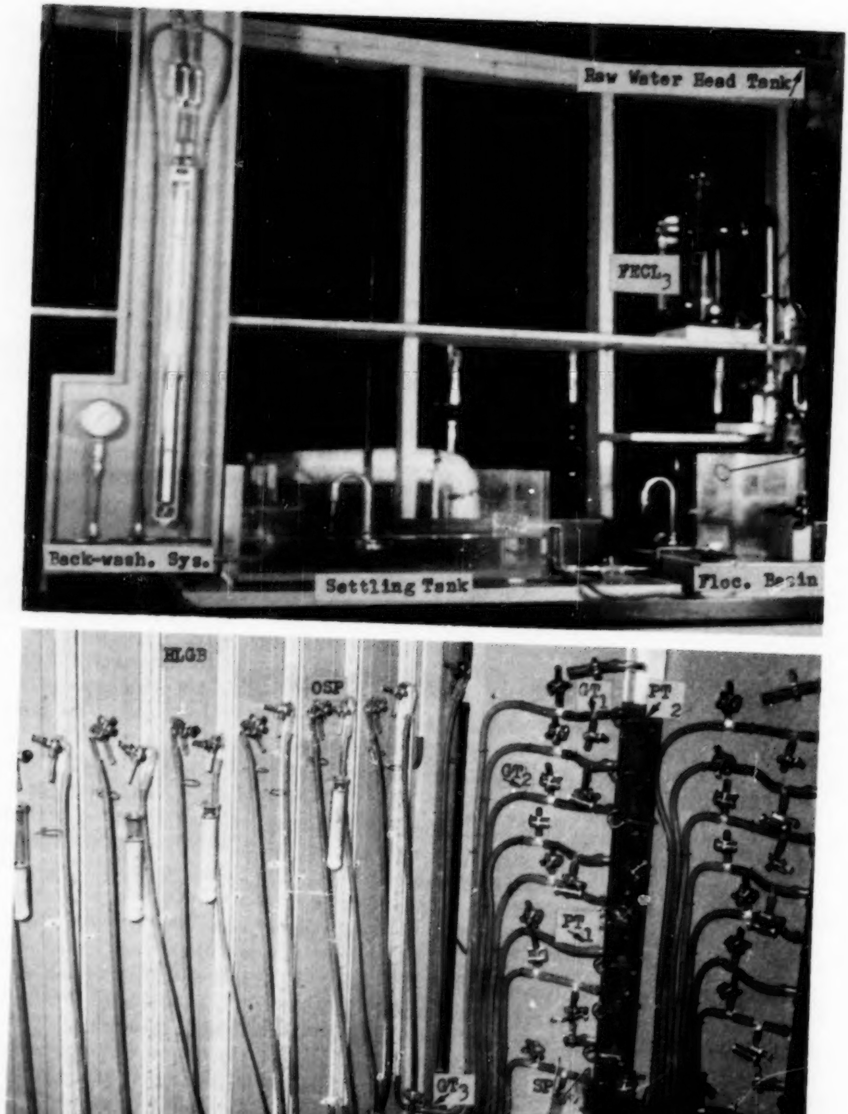

Raw Water Head Tank
FECL3
Back-wash. Sys.
Settling Tank
Floc. Basin
HLGB
OSP
GT1
PT2
GT2
PT1
GT3
SP

Fig. 2

The head at each depth in the filter was indicated by an individual manometer tube. Simultaneous reading of all the manometers could be secured by photography if necessary. The other leg of the third tee was connected to the original sampling point (OSP) which was found inadequate and was not used after the first test.

Another series of 9 piezometer tubes ($PT_2$) were located on the opposite side of each filter. From these tubes, successive layers of sand could be drawn and the storage capacity of each sand layer was determined after each test.

At the bottom of both filters, special-made carborundum porous bottom plates were installed to replace the conventional collecting system. Through a specially-designed rate controller, the filter water was discharged into the drain.

In order to avoid any direct connection from the testing model to the public water supply, a separate washing system was designed. The tap water was discharged to the wash water tank through a water-break. The wash water pump pumped the water directly to the filter. On the discharge side of the wash water pump, a specially-made venturi tube with a U-tube differential gauge and a pressure meter were installed to measure the wash water. The dirty wash water passed over a specially-designed collecting weir at the top of the filter and then discharged to the sewer. Drain, by-pass line, and overflow device were provided for each unit of the model. Great flexibility in model operation could be obtained by proper operation procedures.

The hydraulic similarity of the model was also investigated. As far as the filter is concerned, no theoretical investigation has been made. Glass tube filter models have been used successfully in the past years.(9,11,12) All previous investigators agreed that the results obtained from the glass-tube filter were reliable when compared with those from the large filter units. As a matter of fact, the filter model has the same depth of filter bed, same rate of filtration, and same kind of filtering material as that of the full-scale filter. The model could be considered as a column which was cut from the prototype, or as an actual filter with small area. If the area of the filter is not small enough to create considerable boundary, layer effects, it is reasonable to expect that dependable results could be delivered from the model as well as from the full-scale filters.

In the present research, the filter models have a much larger area than those which were used in the past years. It seems there is no question that the model will give satisfactory results.

Turbidity expressed as parts per million (ppm) has been universally used to indicate the cloudiness of water in the water filtration field. There are several kinds of turbidity-measuring devices which have been used in the water treatment plants such as Jackson-Candle meter, Baylis meter, Hellige meter, etc. Either because of poor accuracy in the low-reading range or the large sample size required, these instruments are not suitable for precise research work on a model scale. As more accurate data was required in this experiment, a Coleman Universal spectrophotometer calibrated against the standard turbidity stock solution was used to determine the turbidity in all samples.

The experimental model was designed on the basis of continuous operation. In order to obtain reliable and consistent data, all procedures of operation were standardized after the preliminary tests. The chemical solutions and the rate of filtration were accurately regulated by the specially-made rate of flow controller. This rate controller was designed based on the principle of

floating orifice and siphon tube. The actual dimensions of these rate-of-flow controllers were determined according to the range of flow to be regulated.

## Experiments

The sand used for this experiment was obtained from the Bay City Sand Company of Bay City, Wisconsin. Sand from the same source has been used in St. Paul, Minneapolis, and many other filtration plants in this area.

Uniform sand, by the definition applied herein, is the sand collected between two consecutive sieve sizes. The average size of the uniform sand was determined as the size equal to the square root of the products of the openings of these two sieves.[13] The average specific gravity of the sand is 2.64 and the average porosity for all sizes is 44.2 per cent.

In order to compare the results from the uniform sand filter with that of the conventional graded sand filter, a control filter of graded sand was tested in parallel to the uniform one. Medium size sand, with effective size of 0.5 mm and uniformity co-efficient of 1.6, prepared as described in the "Tentative Standard Specifications for Filter Material" of the American Water Works Association[14] was used in the control filter.

Before each test, all piezometer tubes and the connecting tubing were flushed by tap water. The manometer readings on the head loss gauge board indicated zero loss of head. Both filters were washed at a rate that expanded the sand to 150 per cent of its original depth, and until the wash water had a turbidity of 5 ppm or less. The wash water was slowly turned off within 1-1/2 minutes to permit the sand to settle to the same depth after each wash.

Before the filter was put into operation, a condition of equilibrium within the system was required. The filter influent was first by-passed around the filter directly to the effluent rate-of-flow controller until the desired turbidity of desired rate was obtained. The turbidity in the filter influent is between 16 to 19 ppm. Head loss gauges were read every hour. Temperature adjustments were made when required to keep variations down to 2°C. The filter run usually terminated when a 7' loss of head in the filter was reached. Extra samples were taken after this time if conditions allowed.

Usually the turbidity readings of the sample and the head loss records were plotted immediately after measurements were completed. Any abrupt changes would indicate a disturbance in the system. An immediate check and proper adjustments would be made when the need was indicated.

### (A) Part I—Study of Sand Size Effect

In order to relate the size effect to the performance of the uniform sand filter, a series of tests with uniform sand of various sizes was made. In all tests, a constant rate of filtration, 2 gal./sq. ft./min., was used and a control filter of graded sand was tested in parallel to the uniform sand filter. The uniform sand and the control filter bed were both 24" in depth.

Every 2 to 3 hours, depending on the length of the filter runs, a series of 6 samples were collected from each filter; namely, the filter influent, sample at 1" depth, 4" depth, 10" depth, 19" depth, and filter effluent. To prevent any appreciable disturbance of the filter bed, one sample at the rate of 10$^{cc}$ per minute was taken at a time. The first 4 minutes of sample was allowed to run to waste to insure that the water standing in the connecting tubing was completely displaced before actual sampling. A minimum of 5 series of samples were required to furnish enough data for the study of the filtering action. Therefore, no sand which had a head loss of 7' in less than 10 hours was

used in this research. After a series of preliminary runs, four sizes of sand were selected for precise study; namely, size of 0.322 mm, 0.383 mm, 0.458 mm, 0.544 mm. A total of 7 complete tests were made for this part of the experiment. (Run 1 to Run 7)

(B) Part II—Study of the Effect of Filtration Rate

After an intensive study of the results obtained from Part I, sand of 0.458 mm and of 0.383 mm were selected for further tests under various rates of filtration.

Five different filtration rates were tested for the sand size of 0.458 mm in this part of the experiment; namely, 1, 2, 3, 4, and 5.5 gal./sq. ft. per minute, and three different rates were tested for the sand size of 0.383 mm. No rate higher than 5.5 gal./sq. ft./min. could be tested in the present model because of the limitations of size of units and the capacity of the pumps. Total of 10 complete tests were run for this part of the experiments. (Run No. 8 through Run No. 17)

(C) Part III—Study of Lag Period

The plant practice has indicated that there is a ripening process which takes place in the filter bed after the filter is first put into service.(15) At the beginning of a filter run, the turbidity in the filter effluent is relatively high. This turbidity gradually decreases to a minimum after a certain period of filtration and then increases. During this period, the sand grains became partly coated, part of the interstices between sand grains is filled with floc and the efficiency of the filter bed is improved.(16) In order to improve the over-all plant efficiency, some operators prefer to waste the filtrate of the first 10 to 20 minutes after the filter is returned to service after back-washing.

The author called the period between the beginning of filtration and the time when the turbidity in the effluent reaches its minimum value (or zero) as the lag period of the filter. If the turbidity in the filter influent is high and the filter run is relatively short, the lag period could be one of the most important factors in the economics of filter operation.

A total of 10 tests were made with 0.458 mm sand at various rates (Run 18 to Run 27). Because of the rapid change of turbidity in the filter effluent, samples taken at 5- to 10-minute intervals were required to furnish sufficient data for accurate study. At such a close sampling interval, sampling along the various depths of the filter bed was impossible; therefore, only the filter effluent was collected in each run. The uniform sand and the control filter were both back-washed at 50 per cent expansion until the turbidity in the waste from the filter became 0.2 ppm or less before the starting of the test.

A test with uncoagulated water (Run 28) was also made under similar conditions. A total of 28 tests were made in this research program. The schedule of tests is as shown on Table I.

## Results and Discussions

In order to study the action taking place within the filter bed, the turbidity removals at different depths in the sand bed of various sizes were plotted on 5 different types of graphs. Because of the limited space, only a part of the results is presented here for illustration.

The first type of graph (Fig. 3) plots the turbidity of the sample at various depths against the time of filter run. In the second type of graph (Fig. 4), the turbidity of the sample was plotted against the depth of the filter bed at various times during the filter run. The results from both the uniform sand filter and the control filter are plotted on the same graph.

The third type of curve (Fig. 5) shows the per cent of turbidity removal per inch of depth in each successive layer vs. the time of filter run. The per cent turbidity removal per inch was obtained by dividing the total per cent of turbidity removal of each layer by its depth, in inches.

In the fourth type of curve (Fig. 6), the per cent of turbidity removal per inch of depth is plotted against the depth of the filter run. Since the per cent of turbidity removal per inch of depth is an average value per inch of each layer, the value is plotted at the center of each layer and the curves are drawn accordingly.

The fifth type of graph (Fig. 7) shows the per cent of turbidity removal per inch vs. the depth for four various sizes of sand at 15 hours after the filtration has started.

(A) The Progressive Action of Filtration

The curves on Fig. 5 show how the rate of turbidity removal varies in each layer of the filter bed during the course of a filter run. For instance, in Run No. 2, the first inch of sand bed removes about 86 per cent of the total applied turbidity at the end of the first hour of filtration. The per cent removal in this layer drops very rapidly during the first 10 hours and approaches zero removal as the filtration continues.

The second layer is 3" deep and extends from 1" to 4" below the surface of the sand bed. The removal in this layer begins at about 5 per cent per inch. Its efficiency increases gradually when the removal in the first layer decreases. The per cent removal in this layer reaches its maximum value of about 19 per cent after 10 hours and then decreases gradually with time. By the end of a run, usually at 7' of head loss, this layer still has a relatively high efficiency in removal of turbidity.

The third layer is 6" in depth and extends from 4" to 10" below the surface of the sand bed. Removal in this layer starts at only about 1 per cent per inch because most of the turbidity is removed by the top layers. The removal in the third layer increases steadily as the top two layers become gradually overloaded. This layer still removes a considerable portion of the turbidity (8 per cent per inch) by the end of the filter run.

The fourth layer is 9" in depth and extends from 10" to 19" below the surface of the bed. No appreciable turbidity is removed in this layer at the beginning of the filter run. As the removal in the top layers decreases, removal in the fourth layer gradually increases. The removal in the bottom layer, extending from 19" to 24" below the surface of the bed, is very little and is practically negligible in this run. Similar curves were obtained in uniform sand filters of different sizes of sand and under various rates of filtration.

The removal in the bottom layer becomes important when a higher rate of filtration and coarser sand are used. The turbidity removal in the graded sand filter shows similar trend.

The results from these studies indicates the upper portion of the bed removes most of the turbidity during the first part of the run. The burden is transferred gradually to the lower portion of the bed as filtration continues. It is mainly due to the fact that, after the upper layers gradually begin to clog

Run No. 2

Turbidity vs Time

(Sand Size 0.888 mm at 2 gal./sq.ft./min.)

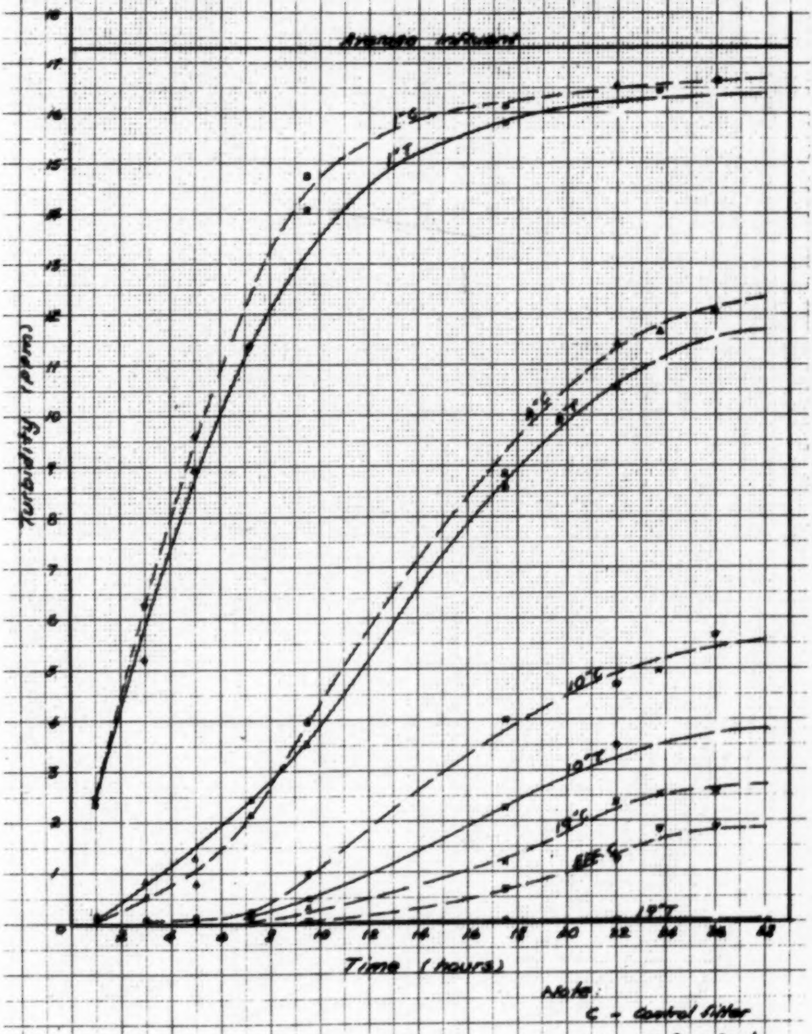



Fig. 3

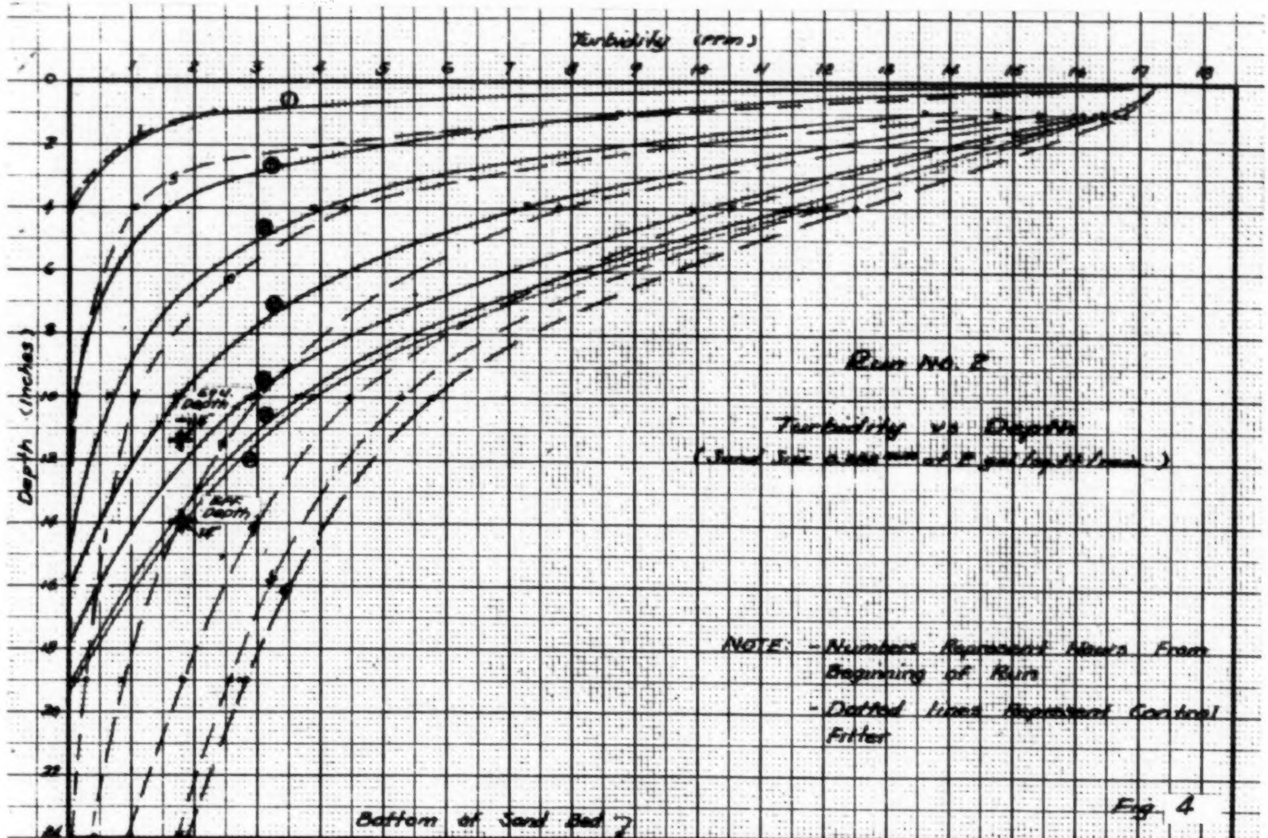

Turbidity (PPM)
Depth (Inches)
Run No. 2
Turbidity vs Depth
NOTE: - Numbers Represent Hours From Beginning of Run
- Dotted lines Represent Control Filter
Bottom of Sand Bed

Fig. 4

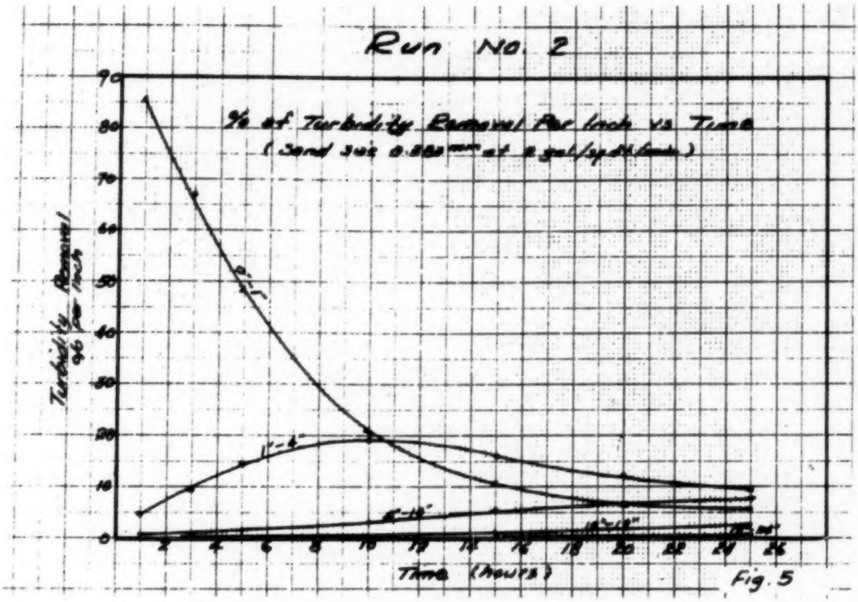

Run No. 2
% of Turbidity Removal Per Inch vs Time
Turbidity Removal % per inch
Time (hours)

Fig. 5

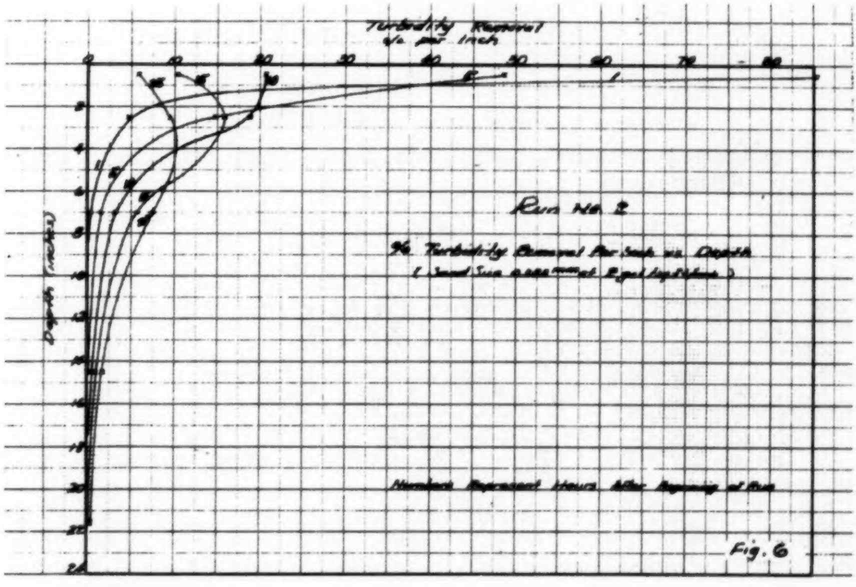

Turbidity Removal % per inch
Run No. 2
Depth (inches)
Numbers Represent Hours After Beginning of Run

Fig. 6

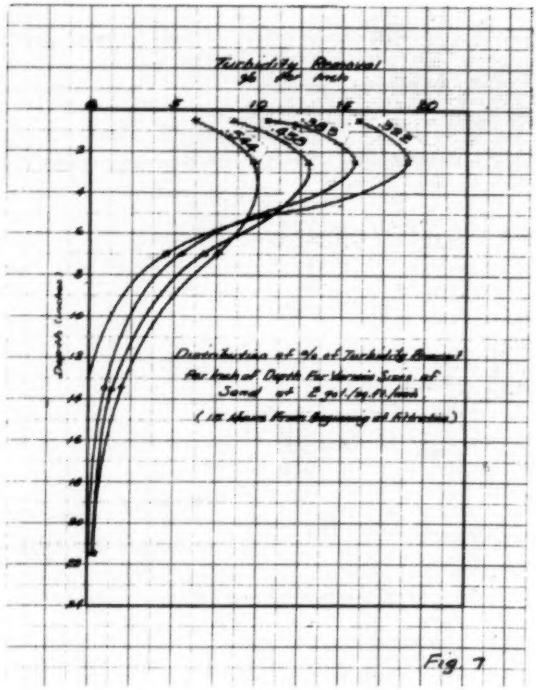

Turbidity Removal
0
5
10
15
20
Depth (inches)

Fig. 7

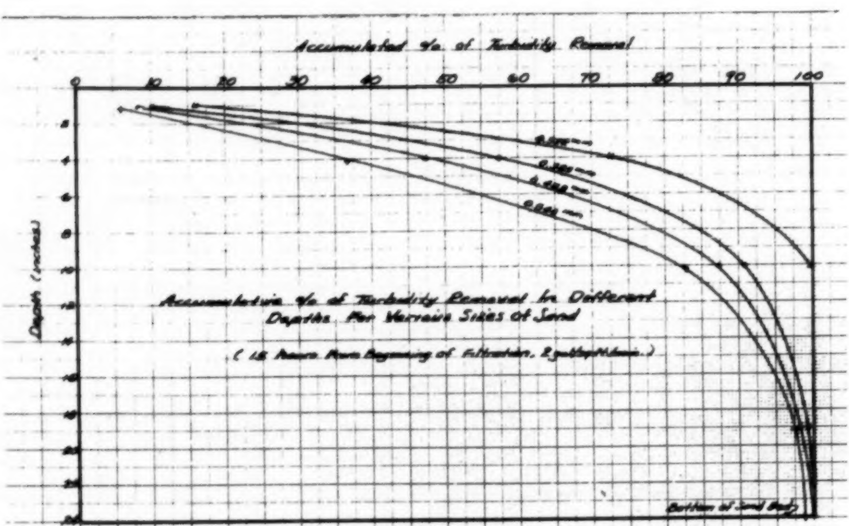

Accumulated % of Turbidity Removal
0
10
20
30
40
50
60
70
80
90
100
Depth (inches)
Accumulative % of Turbidity Removal In Different
Depths For Various Sizes of Sand
Bottom of Sand Body

Fig. 8

up, the higher flowing velocity developed in the upper layers, breaks the attached mass of floc and brings them into the lower portion. The rate of transferring the burden is relatively high for the coarser sands or at higher filtration rates, but the basic action is the same. The filtering action taking place in the graded sand filter is similar to that in the uniform sand filter. Eliassen[10] observed a similar phenomenon when dealing with a graded sand filter at a fixed filtration rate of 2 gal./sq. ft./min. As far as the removal during the whole filter run is concerned, the whole sand bed shares the burden, with the upper portion being more effective.

(B) Turbidity Removal

1. Effect of Sand Size

The curves in Fig. 6 are a typical example to show how the turbidity removal efficiency is distributed in filter beds at different times. The maximum removal takes place in the top layer for considerable portion of the run. The section of maximum removal moves to the second layer after certain period of filtration.

In observing Fig. 7, it will be noted that, in the uniform sand filters of identical depth and after the same period of filtration, the upper portion of the bed of finer sand has a higher per cent removal than that of the coarse sand. The situation is reversed in the lower part of the filter. The low per cent removal in the bottom portion of the finer sand bed is not because the efficiency of this section is less than that of the coarse sand. It is because the upper portion of the finer sand bed has removed most of the turbidity and very little remains in the water which reaches the lower part of the fine sand filter. This can be easily visualized in the accumulative removal curve (Fig. 8), where the accumulative per cent of turbidity removal from the water was much higher for the upper portion of the finer sand bed than for the corresponding layer of the coarse one.

In a graded sand filter, the finer sand grains are always in the top layer due to the hydraulic gradation during the back-washing process. This will explain why the top few inches of sand usually does most of the work in a conventional graded sand filter.

2. Effect of Filtration Rate

From Fig. 9 and other data which are not shown here, it indicates that the per cent of turbidity removal is lower in the top portion of the bed at higher rates of filtration. The higher rate causes deeper penetration of turbidity and also higher per cent of removal in the lower portion. Apparently, the large shear forces due to the high flow-through velocity at a high rate of filtration reduces the removal in the upper portion of the bed. This shear force also dislodges the less strongly-bonded floc collected in the upper portion and carries them into deeper layers.

The size of sand in a uniform sand filter is the same in both the upper and the lower layers. Therefore, the lower portion is as effective as the upper portion in turbidity removal if there is sufficient turbidity passing to it. This will explain why the uniform sand bed usually performs better than the graded sand bed of the same depth under higher rates of filtration.

In each test, microscopic examination of the floc in the sample was made. The average size of the floc in the filter influent is about 10 to 11 microns. The average size of the floc decreases when the sample is drawn from deeper layers. This indicates that the larger floc particles are first removed from the water by the upper layers and the smaller flocs are left to reach the lower portion of the sand bed.

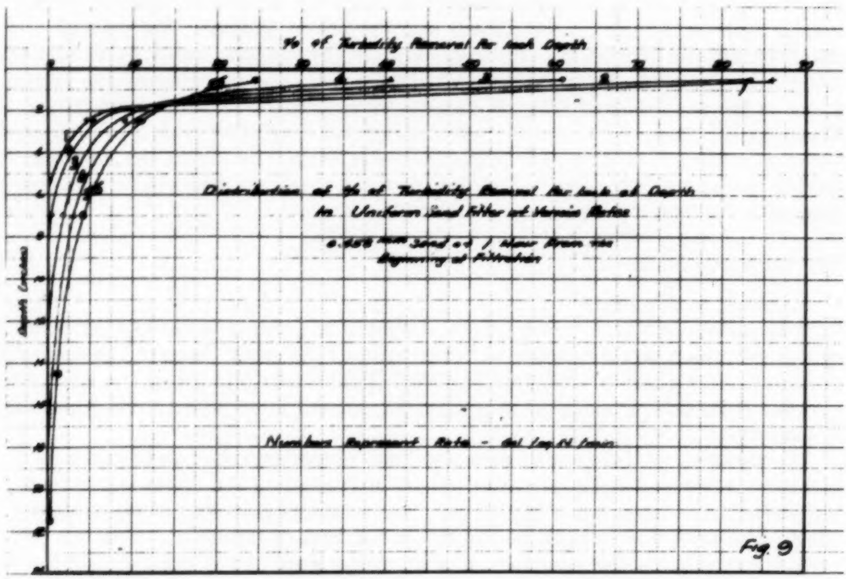
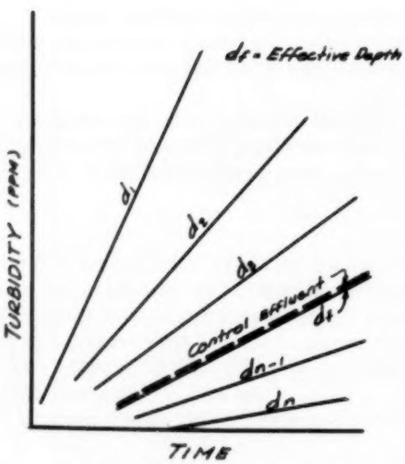
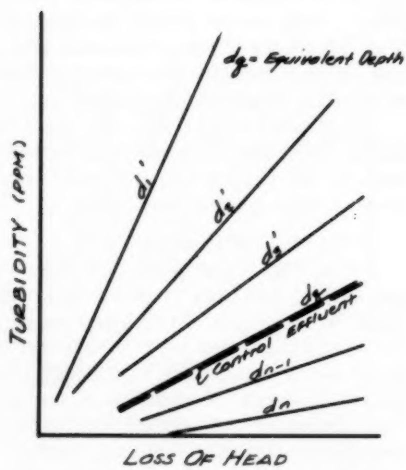



Fig. 9




GRAPHICAL PRESENTATION
OF EFFECTIVE DEPTH
FIG. 10




GRAPHICAL PRESENTATION
OF EQUIVALENT DEPTH
FIG. 11

(C) Equivalent Depth

In observing the curves on Fig. 4, it will be noticed that the turbidity in samples taken from the lower portion of the graded sand bed is higher than that from the same portion of the uniform sand bed after the same period of filtration. If the same turbidity in the effluent is to be maintained for both filters, a shallower sand bed will be required in a uniform sand filter. For instance, on Fig. 4, a depth of about 14" of 0.383 mm uniform sand will remove the same amount of turbidity as a 24" graded sand filter after identical periods of filtration. The author called this depth, (14") the effective depth of the uniform sand filter. This effective depth will be a constant value after the rate of filtration and the size of sand are fixed. From the same figure, it is seen that the effective depth is 14" after 25 hours of filtration, and has approximately the same value at 10 or 20 hours or other times.

It should be pointed out that the rate of change of head loss has not been considered in the development of the terminology "effective depth." From Fig. 12 and Fig. 4, the time required for a total loss of head of 7' in the control filter of 24" in depth is interpolated as 28 hours, and the turbidity in the effluent is about 1.8 ppm at that moment. As mentioned before, an effective depth of 14" of 0.383 mm uniform sand will also give 1.8 ppm of turbidity in the effluent after 28 hours of service. From the same figures, it may be observed that 14" of 0.383 mm uniform sand will have about 11' head loss after 28 hours service. The time required for 7' head loss is only about 17 hours. If the effluent of both filters are sampled at 7' head loss, the uniform filter of 14" depth will have only 0.75 ppm turbidity in the effluent while compared to the 1.8 ppm present in the effluent from the control filter. A 14" depth still seems too deep to deliver the same effluent on the basis of equal head loss. Therefore, a new depth of 11.5" was tried. It was found that the 11.5" depth of 0.383mm of uniform sand bed had a 7' head loss at 18 hours with an effluent of 1.8 ppm turbidity at that moment.

Practically, in comparing the performance of any two filters, it is logical to compare them on the basis of equal head loss and equal turbidity removal. Therefore, the new depth of 11.5" was adopted as a measure for comparing the performance of the uniform sand filter to that of the control filter. The author called this new depth the equivalent depth. A uniform sand filter of equivalent depth will have turbidity removal and loss of head identical with that of a 24" graded sand bed when operating under the same conditions. Theoretically, the equivalent depth could also be explained in the following manner: It is known that there is a definite relationship between turbidity removal and the time of filtration when the characteristics of filter influent, the size of sand and the rate of filtration are fixed (Fig. 3). This relationship could be theoretically simplified as on Fig. 10, where $d_1$, $d_2$, $d_3$, ---$d_n$ represent the distances below the surface of the sand bed. As the relation between the time and the turbidity in control effluent (shown by the dotted line) is fixed after the filtration rate is selected; so there must be a depth, $d_f$, in the uniform sand bed which will deliver approximately the same turbidity as the control effluent at all times. This $d_f$ is theoretically equal to the value which the author has called the effective depth.

As a linear relationship exists between the time and the loss of head, Fig. 23, the time can be expressed in terms of loss of head. Fig. 10 could be redrawn as shown in Fig. 11. By the same reasoning, there must be one depth $d_q$, in the uniform sand bed, at which the turbidity is approximately coincident with the control filter effluent at any value of loss of head. This depth, $d_q$, will be theoretically identical to the equivalent depth.

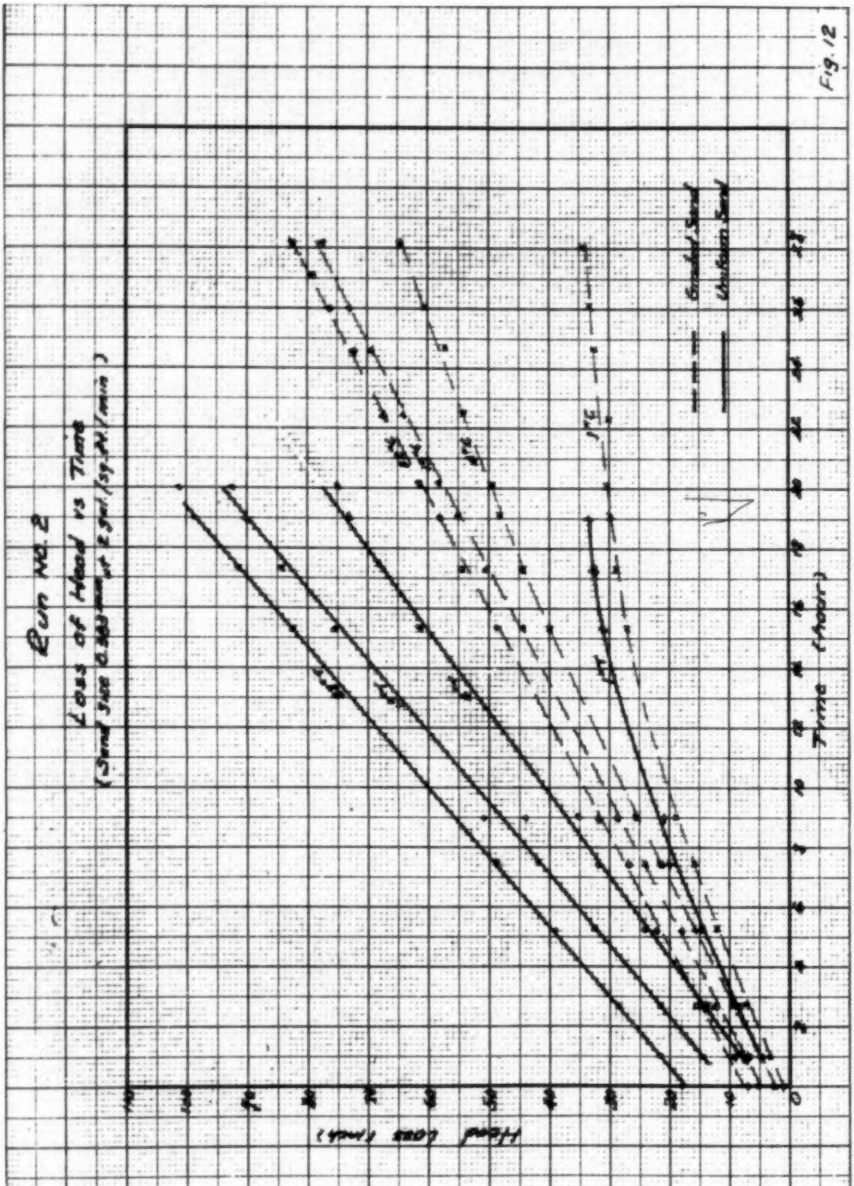


Fig. 12
Run No. 2
Loss of Head vs Time
Time (hour)
Head Loss (inch)
Graded Sand
Uniform Sand

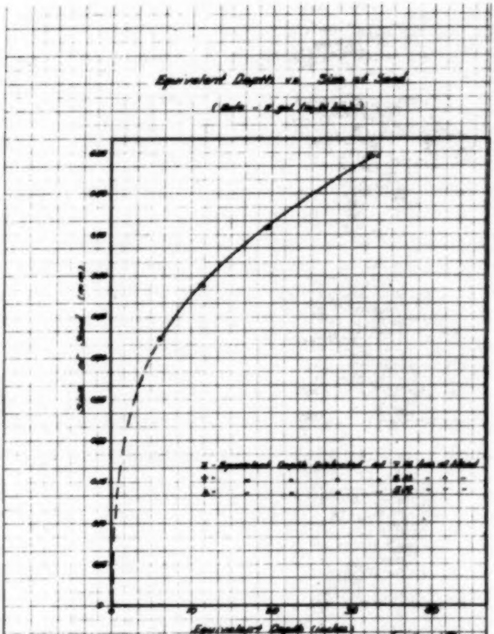

Equivalent Depth vs. Size of Sand
10
20
30
40
Equivalent Depth (inches)

Fig. 13

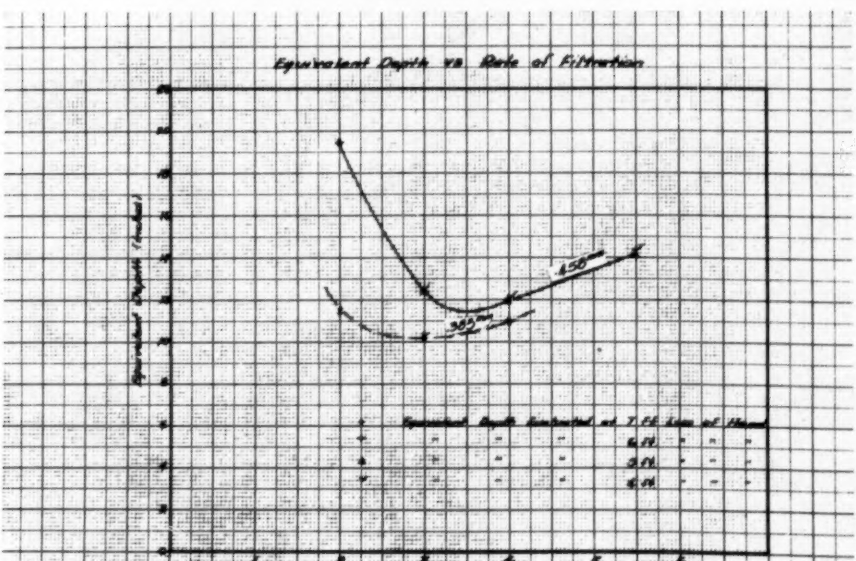
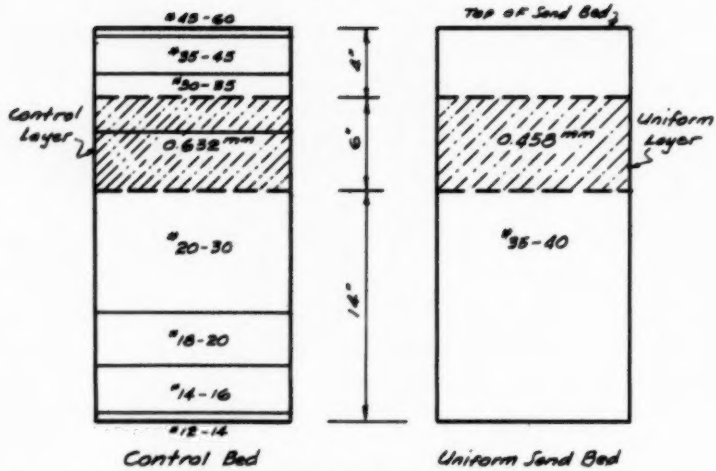

Equivalent Depth vs Rate of Filtration
.458 mm
.385 mm
1
2
3
4
5
6
Rates
Equivalent Depth (inches)

Fig. 14




COMPOSITION OF BEDS

Fig 15

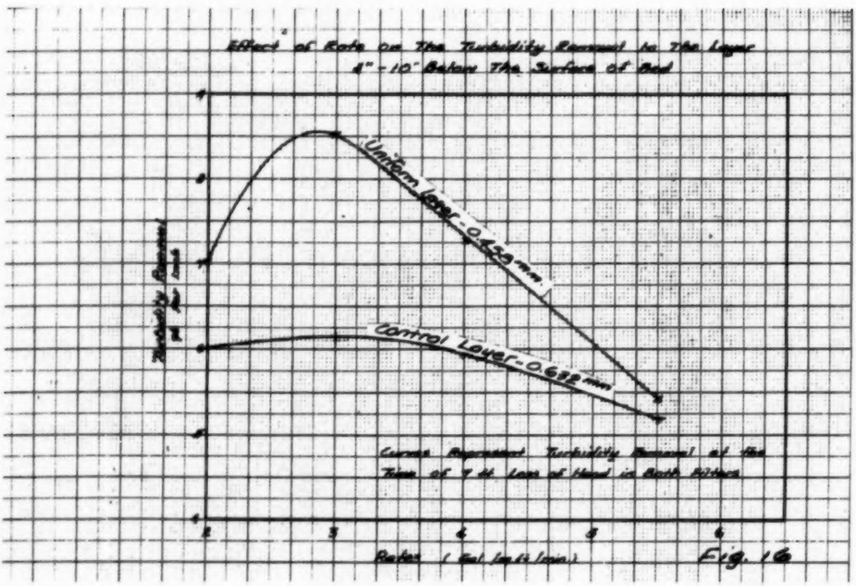



Fig. 16

The above discussion indicates that the equivalent depth will be a constant value at any loss of head. This was also proved from the analysis of the experimental data. The equivalent depth of different sizes of sand and under various rates of filtration may be evaluated at various losses of head. The results are plotted on Figs. 13 and 14 which show that the equivalent depth at various values of head loss has practically the same value.

Fig. 13 shows that the equivalent depth increases with the size of the sand grains. The dashed line represents the extension of the curve and indicates that it probably passes through the origin. That means that when the size of sand approaches zero, it can be considered as an impervious media. A very thin layer (almost zero depth) of very fine sand would give the same head loss and have the same turbidity removal as the 24" control filter.

The change of the equivalent depth due to the variation of the filtration rate (Fig. 14) can be theoretically explained as in the following paragraphs.

The composition of the sand beds in the two filters tested under various filtration rates are shown in Fig. 15.

A layer of 6" depth which extends from 4" to 10" below the surface of the sand bed is selected for the comparison. The reasons for choice of this layer are:

1) This layer is immediately above the layer wherein the equivalent depth falls. The performance of this layer will directly influence the evaluation of the equivalent depth.
2) The top surface of this layer is 4" below the surface of the bed; consequently, any effects due to uneven distribution of hair cracks or momentary variation of the turbidity of the filter influent will not affect the normal performance of this layer.
3) This layer is not too deep within the bed. Samples from this layer still contain enough turbidity for precise analysis.

The average size of sand in this layer of the control filter is 0.632 mm and 0.458 mm in the uniform sand filter. The former is called the control layer and the latter, the uniform layer.

It has already been pointed out that the filtering efficiency is improved when the sand grains are partly coated with the suspended matters. The author further believes that the finer sand grains are relatively easier to be coated because of their larger contact surface per unit volume; therefore, the improvement of the efficiency in turbidity removal will be faster. It is evident that more suspended matter will be brought into the lower layers when the filtration rate is increased from 2 to 3 gal./sq. ft./min. In the uniform layer, the sand is finer and most of the turbidity has been removed from the water after passing through this layer. Thus, the efficiency is rapidly improved as the sand grains become coated. In the control layer, the efficiency is also improved but not as much as in the uniform layer because of the coarser sand. In both filters, the turbidity in the final effluent is greater at the rate of 3 gal./sq. ft./min. than that at 2 gal./sq. ft./min., but the performance of the uniform sand filter is better than the control filter because its lower portion has contributed more removal. The evaluation of the equivalent depth is based on the relative difference between the performances of the two filters; therefore, the equivalent depth of the uniform sand bed is reduced when the rate is raised from 2 to 3 gal./sq. ft./min.

When the rate is increased above 4 gal./sq. ft./min., more suspended matters will pass through the filter per unit time. Because of the relatively higher filtering efficiency in finer sand, the sand grains in the uniform layer

became quickly coated. Since the initial voids are practically the same in both control layer and the uniform layer, the heavy coatings in the uniform layer reduce the area for water passage in a relatively short time. Then, the flow through velocity in the uniform layer is rapidly built up and its efficiency drops after a short period of filtration. On the contrary, the control layer, at this time, is still gaining efficiency because the sand grains are only partially coated. This explains why the equivalent depth increases when the filtration rate is higher than 4 gal./sq. ft./min.

The above theoretical discussions were proved from the experimental data. Fig. 16 shows the per cent of turbidity removal per inch in both the control layer and the uniform layer vs. the rate when the loss of head is 7'. As the rate is raised from 2 to 3 gal./sq. ft./min., the per cent removal of both layers are improved, but the uniform layer improves much faster. This explains why the equivalent depth is reduced at 3 gal./sq. ft./min.

After this peak, the uniform layer loses its efficiency more rapidly than the control layer. In the uniform layer, a small increase in the rate will considerably reduce the per cent removal. Therefore, the relative efficiency of the uniform sand bed is rapidly reduced and the equivalent depth increases. Even though the efficiency drops rapidly in the uniform layer, the per cent removal is still higher than the control layer. This explains why the equivalent depth increases, but still remains less than the 24" depth of the control filter.

If a finer sand, 0.383 mm, is used, the equivalent depth will be less. The results are shown on Fig. 14. On Fig. 14, the equivalent depths for 0.458 mm are 19.5" and 12.5" at the rate of 2 and 3 gal./sq. ft./min., while the equivalent depths for 0.383 mm are 11.5" and 10.2" at the same filtration rates.

(D) Loss of Head

1. Loss of Head and Time of Filtration

A review of the curves on Fig. 12 and results from other runs indicates that the loss of head in every test varies approximately as a straight line with time except for the top 1" of depth.

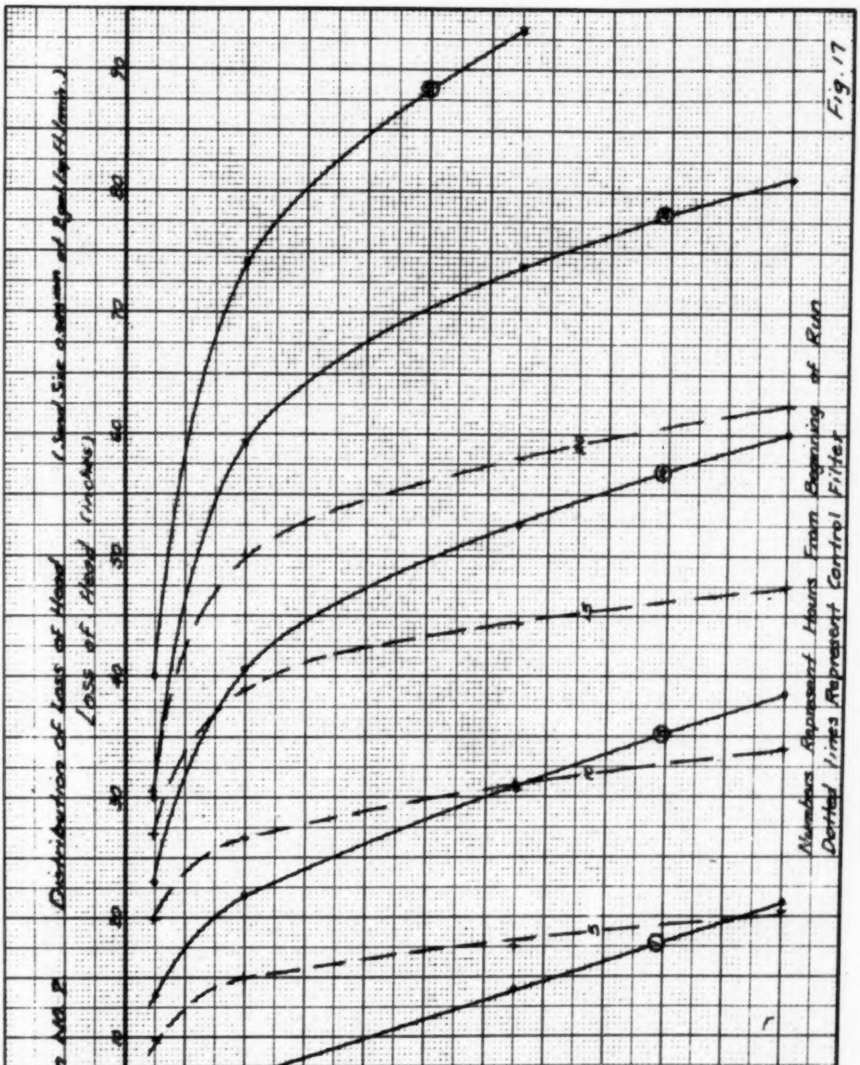
In the top 1" of sand, the rate of increase of head loss is gradually reduced during the last part of the filter run. The reason for this probably is due to the hair cracks which develop in this layer after a period of filtration.

2. Distribution of Loss of Head in Filter Bed

In looking at the curves on Fig. 17, it will be noticed that most of loss of head in the control filter is caused by the top few inches of sand. In the uniform sand filter, the distribution of head loss is more uniform through the whole bed. The lower portion of the bed also contributed an appreciable amount of head loss, especially in the bed of coarse sand. The per cent of loss of head in the first inch of depth at the total loss of head of 4', 7', and 8' was plotted against the sand size as shown on Fig. 18. A linear relationship is approximated. It indicates that about 20 to 50 per cent of the total head loss occurs in the first inch of sand for sand sizes from 0.55 mm to 0.3 mm.

The average head loss in the first inch of the control filter is about 40 per cent at a total loss of head of 7' from Fig. 18; a 40 per cent of head loss in the first inch results from using a uniform sand of 0.37 mm. The actual average size in the first inch of the graded sand bed was approximately 0.384 mm. These two values check quite closely.

The distribution of head loss in the bed of 0.458 mm at various rates of filtration is shown on Fig. 19. The per cent of head loss in the top one inch


Run No. 2
Distribution of Loss of Head
Loss of Head (inches)
Depth (inches)
Numbers Represent Hours From Beginning of Run
Dotted lines Represent Control Filter
Fig. 17

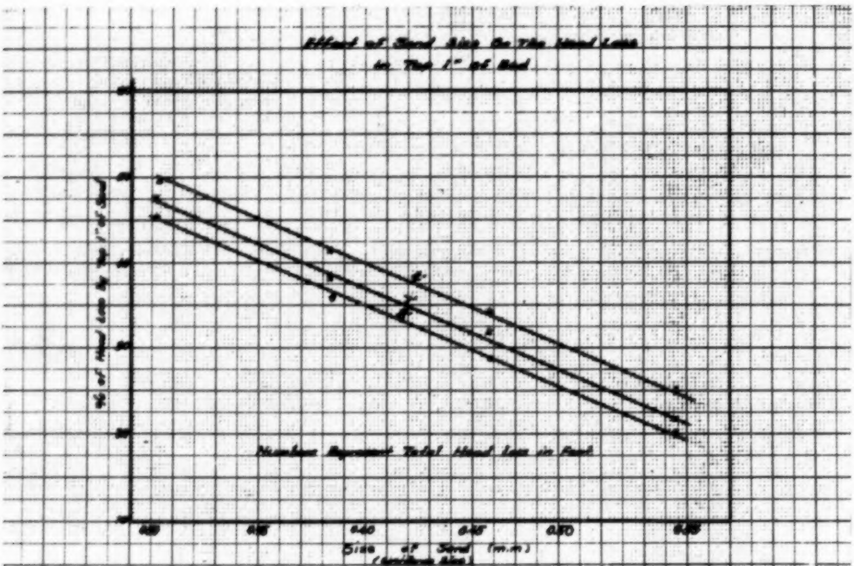

Effect of Sand Size On The Head Loss
in Top 1" of Bed
Numbers Represent Total Head Loss in Feet
Size of Sand (m.m)

Fig. 18

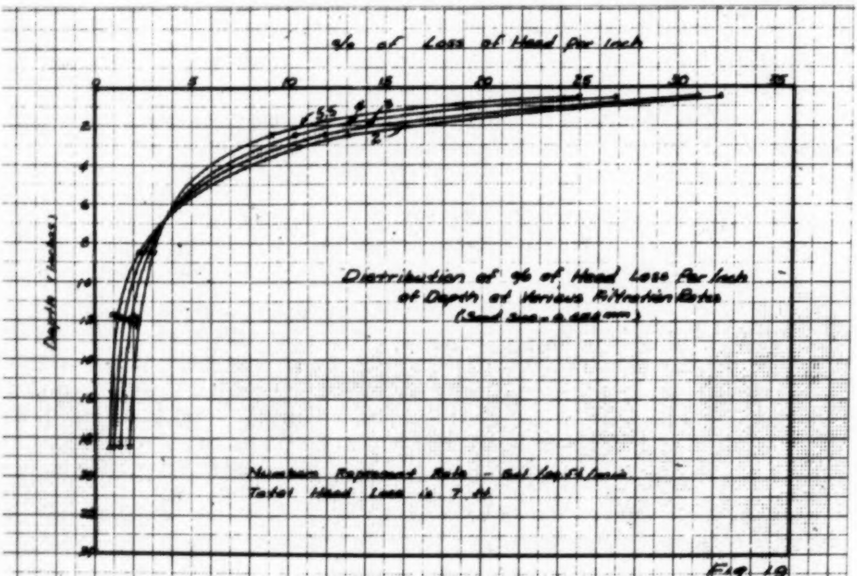

% of Loss of Head per inch
Depth (inches)
Distribution of % of Head Loss Per Inch
of Depth at Various Filtration Rates
Total Head Loss is 7 ft.

Fig. 19

of depth decreases as the rate of filtration increases. The changes of head loss in the first inch due to the variation of rate of filtration are not as much as that due to the variation of sand size. It drops 7 per cent when the rate is increased from 2 to 5.5 gal./sq. ft./min.

3. Loss of Head and Turbidity Removal

It is already known, the loss of head when clear ter is filtered through a layer of sand, remains almost constant and the head loss continuously increases when coagulated water is used. Apparently, the increase of loss of head is related to the removal of this coagulated material from the water. If a comparison is made between the per cent of head loss per inch (Fig. 20) and that of the turbidity removal (Fig. 6) it will be noticed that the per cent of head loss in the upper portion of the bed increases from the beginning to the end of the run, while the per cent of turbidity removal of the same layer continuously decreases. The head loss increases at a nearly constant rate, regardless of the reduction in turbidity removal. This would tend to indicate that the change of head loss in the filter is not directly proportioned to the amount of turbidity removal.

The main factor to cause the nearly constant increase of head loss, especially when the turbidity removal is low, probably is due to the change in porosity of the filter bed. From the equation developed by Fair[17], the head loss varies as $(1-f)^2/f^3$ where f is the porosity of the sand bed. During the latter part of a filter run, a very small amount of turbidity deposited in the upper portion of the bed will produce a negligible effect on the shape, size of sand, but its effect on the porosity will be considerable, as the porosity is already at a very small value. For instance, with a unit decrease of porosity when the porosity is 44 per cent, the value $(1-f)^2/f^3$ increases only 7 per cent while the value $(1-f)^2/f^3$ increases about 40 per cent when the porosity is only about 10 per cent.

4. Effect of Sand Size and Filtration Rate on Head Loss

The effect of sand size and filtration rate on the distribution of head loss in the uniform sand filter was shown on Fig. 21 and Fig. 19. These figures indicate that the head loss in the upper portion of a uniform sand bed increases as the size of sand becomes finer and the head loss decreases as the filtration rate increases.

It is already known that a small change in porosity will produce a considerable effect on the change of loss of head. In a uniform sand filter, more suspended matter is deposited in the upper portion of the bed of finer sand (See Fig. 25). Based on equal initial porosity, the upper portion of the finer sand bed has a lower final porosity at the time of 7' head loss. The curves on Fig. 7 illustrate that the upper portion of the finer sand accomplishes greater turbidity removal. The combined effect of the higher removal and the lower final porosity explains why the upper portion of the finer sand bed contributes a higher per cent of head loss. From Fig. 27 and Fig. 9 with the same reason, the higher per cent of head loss in the upper portion of filter operated at lower rates will also be explained.

5. Effect of Sand Size on the Length of Filter Run

As a basis of comparison, the length of filter run used in this experiment is defined as the time (hours) required to show 7' loss of head in the filter bed. The length of the filter run vs. the sizes are plotted on a log-log scale in Fig. 22. The time required for 5, 6, and 8' of head loss are also shown on the same figure. The relationship between the length of filter run and the size can be mathematically expressed as,

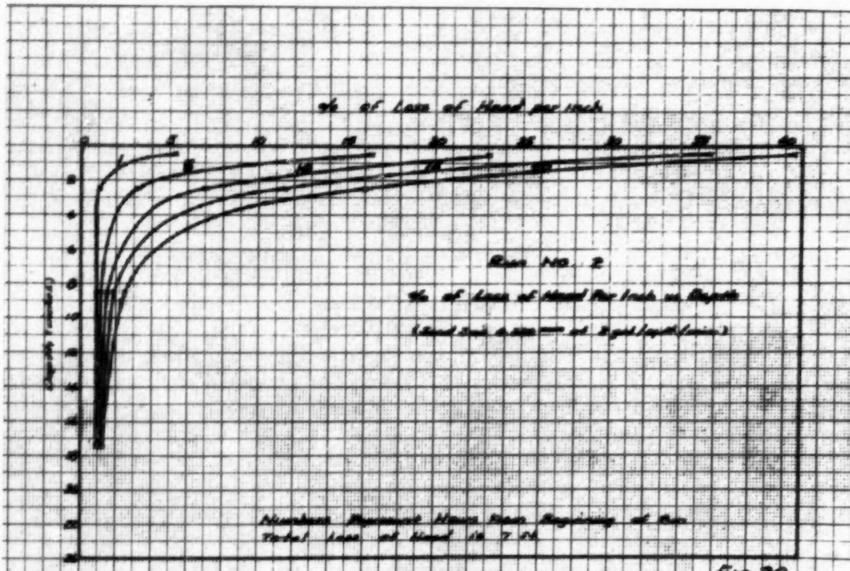

% of Loss of Head per Inch
Run No. 2
Total Loss of Head is 7 ft

Fig. 20

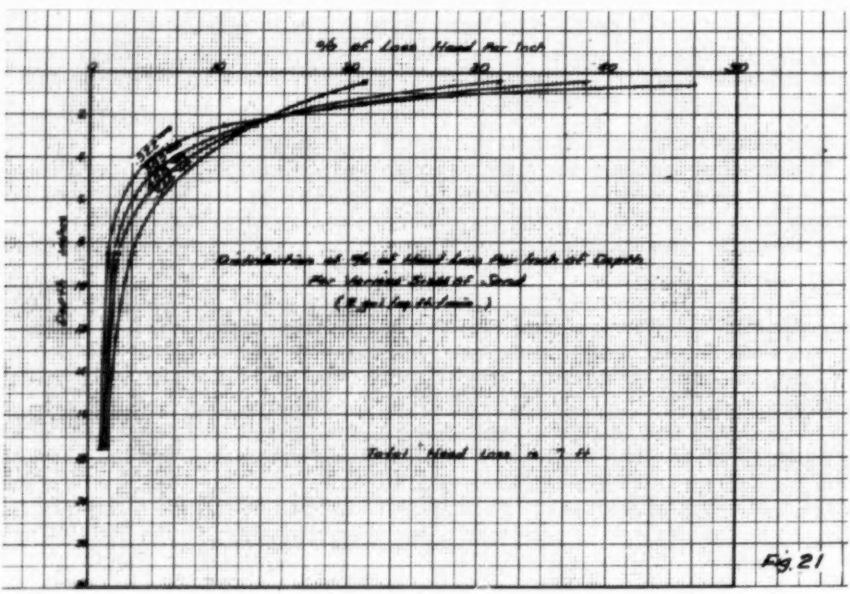
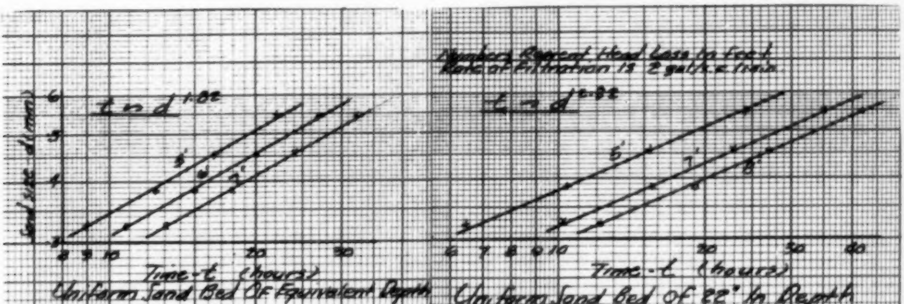
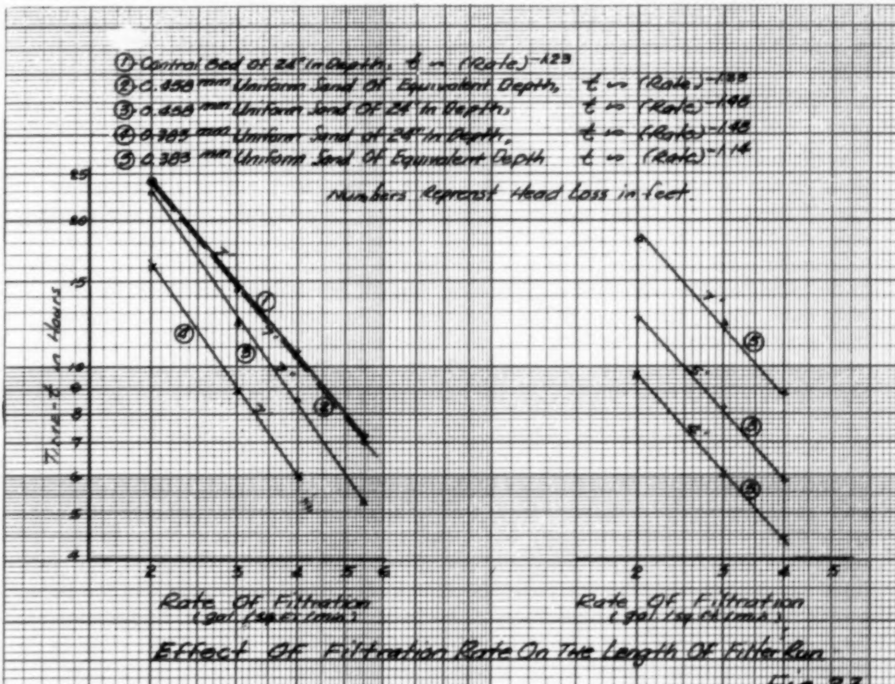

% of Loss Head Per Inch
Total Head Loss is 7 ft

Fig. 21



Effect Of Sand Size On The Length Of Filter Run

Fig. 22



Effect Of Filtration Rate On The Length Of Filter Run

Fig 23

for 22" uniform sand bed, $t \backsim d^{2.32}$
for equivalent depth, $t \backsim d^{1.82}$
where t is the length of filter run in hours
d is the average diameter of sand in mm

The slope of the straight line does not change when the filter run is evaluated at head loss of other than 7'. This indicates that this relationship remains true at other values of head loss.

6. The Effect of Filtration Rate on the Length of Filter Run

The effect of filtration rate on the length of filter run is shown on Fig. 23. A study of this figure reveals that the straight line for 24" of 0.458 mm of uniform sand is parallel to the line of 24" of 0.383 mm. This indicates that the relation between the filter run and the rate of filtration is not affected by the size of the sand in beds of equal depth. The value used to terminate the filter run also does not affect this relationship because the lines are parallel to each at 4', 5', and 7' head loss. The relationship between the length of the filter run and the rate of filtration could be mathematically expressed as,

for 24" graded sand bed, $t = 1/r^{1.23}$
for 24" uniform sand bed, $t = 1/r^{1.48}$
For uniform sand bed of 0.458 mm at equivalent depth, $t = 1/r^{1.23}$
for uniform sand bed of 0.383 mm at equivalent depth, $t = 1/r^{1.14}$
where t is the length of filter run in hours
r is the filtration rate in gal./sq. ft./min.

It is evident that the total loss of head through the filter will change when the depth of the bed varies. Because the length of the filter run is a function of loss of head, so the filter run is also affected by the change of depth of filter bed. As already pointed out, if the depth of the bed remains the same, the relationship between the filter run and the rate of filtration will not be affected by changing the size alone. When the equivalent depth is used in the uniform sand filter, the depth of the filter will vary according to the size used. This may explain why the length of the filter run varies inversely as 1.23 power of the rate when the equivalent depth of 0.458 mm sand is used, and inversely as 1.14 power of the rate for the equivalent depth of 0.383 mm.

(E) Storage Capacity

In this experiment, the storage capacity of a layer of sand is defined as the amount of suspended matter, expressed as per cent by weight, caught by such layer during the complete filter run. The distribution of the storage of the suspended matter in a uniform sand bed of various sizes is shown on Fig. 24. More storage is found in the upper portion of the finer sand beds. In the portion 6" or more below the surface of the beds, the coarser sand bed shows more storage. This is not because the storage capacity of the finer sand is reduced in the lower portion. It is due to the fact that the upper portion of the finer sand removed most of the suspended materials before they have the chance to reach the lower portion. This phenomenon is graphically illustrated on Fig. 25. If the curves on Fig. 24 are extended until they are tangent to the vertical axis, it will be noticed that the deeper penetration of flocs occurs in the bed of coarser sand.

In Test Run No. 6 no turbidity was found in the samples which were taken from layers 10" or more below the surface of the bed of 0.322 mm. In the same filter, the storage of the suspended matter was distributed along the whole depth of the bed (Fig. 24). This tends to indicate that the zero turbidity

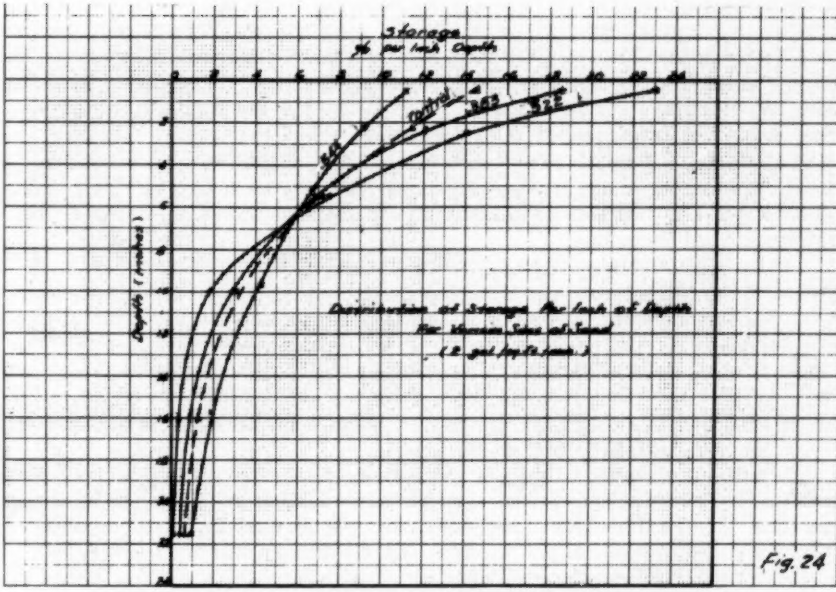

Storage
% per inch Depth
Depth (inches)
Control
Distribution of Storage Per Inch of Depth
For Various Sizes of Sand

Fig. 24

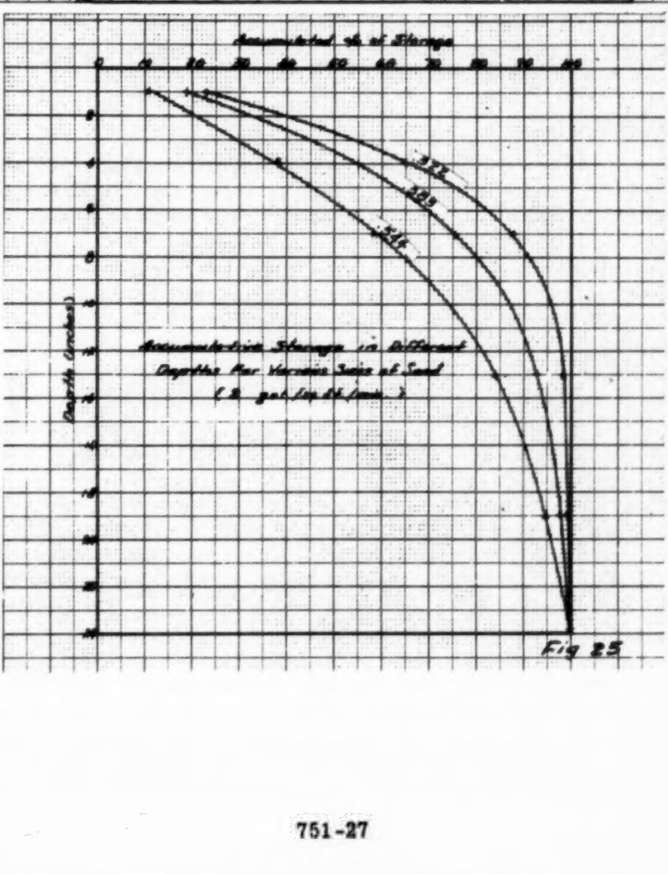

Accumulated % of Storage
0
10
20
30
40
50
60
70
80
90
100
Depth (inches)
Accumulative Storage in Different
Depths For Various Sizes of Sand

Fig 25

in the sample at certain depth of a filter does not mean that the suspended matters in the water have not penetrated to such a depth. The zero turbidity simply means that the concentration of the suspended material in the sample is too minute to be detected at the moment of sampling. The accumulation of these small amounts of suspended matter during the whole filter run will be great enough to be measured in the determination of the storage capacity.

The effect of filtration rate on the distribution of the storage of the suspended material in a uniform sand filter is shown on Fig. 26 and Fig. 27. It seems logical that deeper penetration of the suspended matter occurs at the higher rates of filtration.

The turbidity of the sample is mainly caused by the small particles suspended in the water. In this research, optical reflection of such suspended particles (Nephelometric reading of the Spectrophotometer) was used to measure the concentration of the turbidity in the sample. Actually, both the Nephelometric determination and the storage capacity deal with the same suspended material. Therefore, the storage of the suspended matter in various layers of the filter could serve as another means of checking the performance of the filter in turbidity removal.

The amount of turbidity removal by a filter at any moment could be considered as the difference in turbidity between the influent and the effluent at that moment. The total amount of turbidity removed by each layer of sand bed during a complete run can be obtained by integrating these momentary removals graphically from the curves plotted with turbidity vs. time. Since different units were used in these two methods, the results were converted into percentage basis for comparison. It was found that results from these two entirely independent measurements check closely in each test.

(F) Lag Period

In conducting the tests for the study of lag period, the filter was washed until the turbidity in the waste was 0.2 ppm or less. Further washing seems not to improve the quality of the waste water to any degree. The results for the uniform sand bed of 0.458 mm at the equivalent depth under various rates of filtration are shown on Fig. 28. It shows that the turbidity in the filter effluent begins at a very low value and increases rapidly as the filtration continues. After the turbidity has reached its maximum value, it begins to decrease gradually. A minimum turbidity is obtained after certain period of continuous service. This minimum value may or may not be zero depending on the size of sand and the rate of filtration. A long time is required to obtain a zero turbidity in the effluent at higher filtration rates. In the present experiments, the effluent never reached zero turbidity at the rate of 4 gal./sq. ft./min. or higher.

At the beginning of the test, no visible floc could be seen in the sample, under 100-power microscope. Flocs similar to that in the filter influent were definitely identified in the effluent samples which were taken at the time of maximum turbidity. At higher filtration rates, a higher peak value is obtained, and a shorter time is required to reach this peak. The time theoretically required for the turbidity in the influent to reach the point of sampling was also calculated. This theoretical time practically coincided with the time of peak turbidity in each test (See Fig. 28). Similar results were found for the control filter. This phenomenon together with the data from the test of uncoagulated water, indicates that peak turbidity in the effluent is caused by the suspended matter from the influent and that the filtering efficiency gradually improves as soon as the influent has passed through the filter. Tests

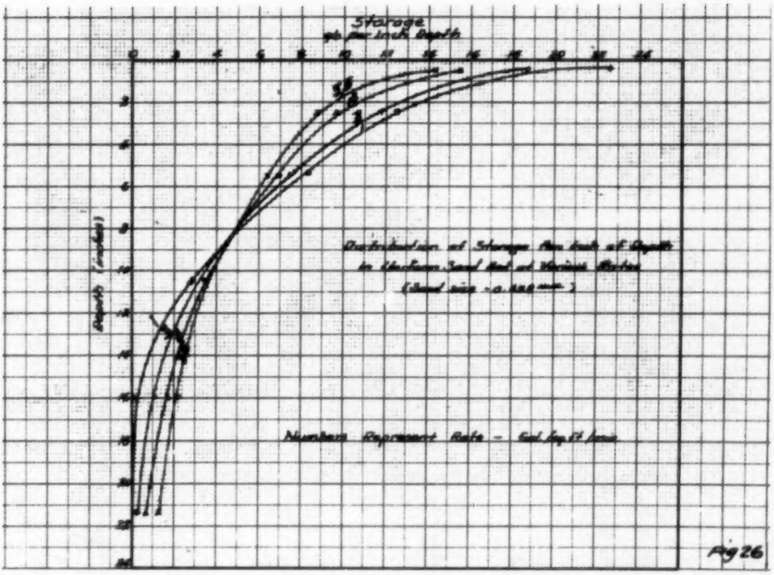

Storage
Depth (inches)

Fig 26

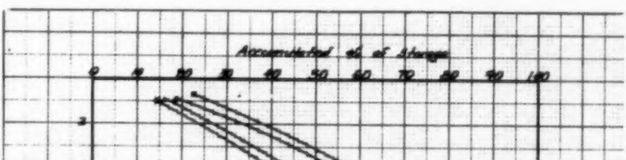

Accumulated % of Storage
0
10
20
30
40
50
60
70
80
90
100
Accumulative % of Storage
in Various Depths at
Different Rates
Depth (inches)

Fig. 27

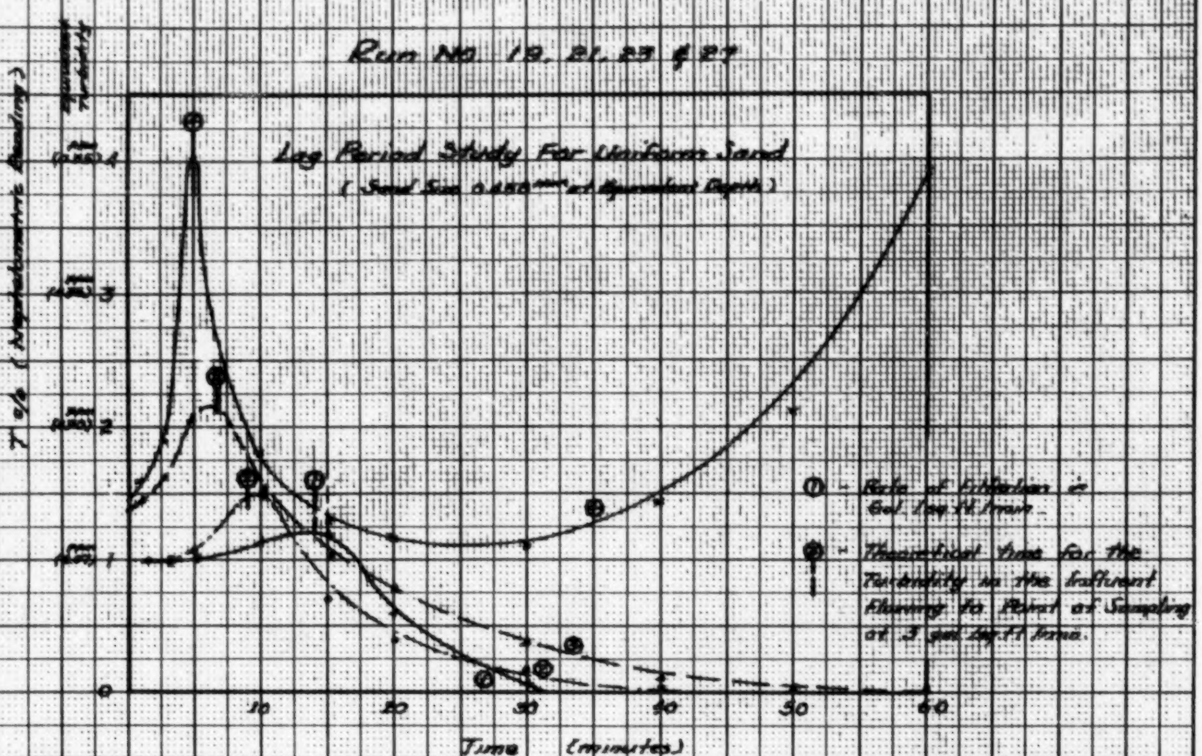

Run No. 19, 21, 23 & 27
Lag Period Study For Uniform Sand
Time (minutes)
0
10
20
30
40
50
60
1
2
3
4
Rate of Filtration in Gal./sq.ft./min.
Theoretical time for the Turbidity in the Influent Flowing to Point of Sampling at 3 gal./sq.ft./min.

Fig. 28

conducted on full-scale filter at the Fridley Filtration Plant of Minneapolis also showed the similar tendency. The lag periods obtained from this experiment are all less than one hour. The peak turbidity is only about 0.5 ppm when the rate is as high as 4 gal./sq. ft./min. The relatively short lag period when compared to the total length of filter run plus the low peak turbidity, makes the effect of the lag period to the over-all plant removal not as important as it was thought before.

(G) Test of Uncoagulated Water

In every test of this research, except at very high rates or those tests conducted to study the lag period, the turbidity in the filter effluent was recorded as zero during the first few hours of filtration. The turbidity gradually increases during the last part of the run. If one considers this phenomenon and those observed during the study of the lag period, it clearly indicates that the turbidity in the filter effluent increases rapidly to a maximum value within a few minutes after the filter is first put into operation. After this peak, the turbidity gradually decreases to a minimum value, then it slowly increases again until the filtration is ended for back-washing. Actually, the filter effluent only represents one of the samples taken at various depths of the filter bed. Similar changes in turbidity could be expected at any depth in the filter.

To obtain a complete picture of the changes in turbidity at various depths in a complete run, a test of uncoagulated water was made. The samples in the first hour of filtration were collected for the lag period study and then sampling at various depths of the sand bed was continued for two days. The results, as plotted on Fig. 29 indicate that the changes in turbidity of samples at various depths of the filter bed have a pattern similar to that of the effluent. Since the top layer has the first chance to get into action, the changes will be completed there earlier than in other layers.

Fig. 29 shows that the changes in turbidity in the first one inch of depth was already completed before the first sample was taken. The completion of the changes are slower toward the lower portion because it requires time to transfer the filtering action from the top to the bottom layers. The minimum value of turbidity in the second layer which extends from 1" to 4" below the surface of the bed was obtained approximately after 6 hours of filtration with about 10 hours being required for the third layer, etc. Similar process was carried out in the control filter, but at a slower rate. This is because the sand grains of the control filter are coarser than the corresponding layer of the uniform sand bed.

Fig. 29 gives a complete picture of the actual filtration process taking place at various depths of a rapid sand filter during a complete run. Since coagulated water was used in all other tests, the lag period can be considered to have ended before the first sample was taken. Therefore, the data obtained, except those tests for the study of the lag period, only represent the last part of the curves as shown by the heavy dotted lines on Fig. 29. (Compare Fig. 29 to Fig. 3)

## CONCLUSIONS

This experiment is a basic research of rapid sand filtration through uniform size of sand. The results are presented with no thought of finality. Based on the results of the limited tests conducted in this experiment, the following conclusions were drawn:

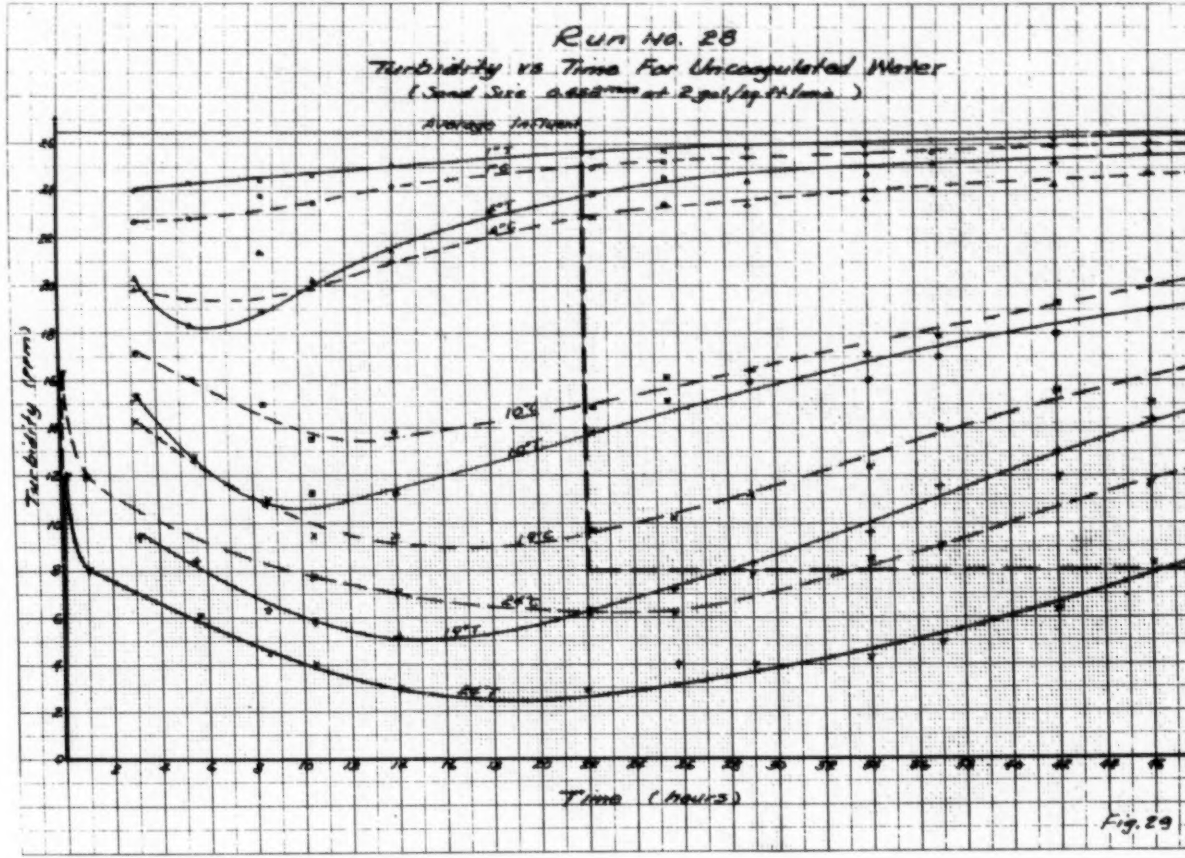

Run No. 28
Turbidity vs Time For Uncoagulated Water
Average Influent
Turbidity (ppm)
Time (hours)

Fig. 29

1) The filtering mechanism in a uniform sand filter is similar to that in the graded sand filter. The upper portion of the bed removes most of the turbidity during the first part of the run. The removal burden is gradually transferred downward as the filtration continues. This basic action is not affected by the variation in size of sand or the change in the rate of filtration.
2) When a clean filter is placed into service, the turbidity at any depth in the filter bed begins at a low value, and increases to a peak when the turbidity in the influent reaches the point of sampling. A greater peak value is obtained at higher filtration rates. The filtering efficiency gradually improves after this peak, and the turbidity decreases to a minimum value as the filtration continues. After this minimum value, the turbidity slowly increases until the filtration is stopped for back-washing.
3) In uniform sand filters of the same depth, the upper portion of the bed of finer sand performs a higher per cent of turbidity removal when the filters are operated at the same rate of filtration. In two identical uniform sand filters, the upper portion of the filter operated at lower rate will perform better removal. The per cent removal in the lower portion is just the reverse.
4) Higher per cent of head loss was found in the top portion of a uniform sand filter bed which was composed of finer sand or operated at a lower filtration rate. The opposite conditions prevail in the lower portion.
5) There was developed from this research, the concept of equivalent depth which is defined as the depth of the uniform sand required to have turbidity removal and loss of head identical with the control filter under the same operating conditions. The equivalent depth increases as the size of sand becomes coarser, and is reduced when the filtration rate is raised. After a minimum value is passed, the equivalent depth gradually increases with the filtration rate.
6) The rate of change in head loss is approximately constant in both the uniform sand filter and the graded sand filter. The head loss contributed by various layers in a uniform sand filter are more evenly distributed than those in a graded sand filter. About 20 to 50 per cent of the total head loss is contributed by the top first inch of sand in the size range from 0.544 to 0.322 mm.
7) In the uniform sand filter, the length of the filter run (hours) varies directly approximately as the 2.32 power of the sand size (mm) and inversely as 1.48 power of the filtration rate (gal./sq. ft./min). The relationship between the filter run and the rate seems not to be affected by the variation of sand size if the depth of the bed remains the same.

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## TABLE I

## SCHEDULE OF TESTS

| Run No. | Filter | Sand Size mm | Filtration Rate Gal./Sq.Ft./Min. | Depth of Bed |
|---|---|---|---|---|
| **Part I - Study of Sand Size Effect** | | | | |
| 1 | Control | Graded | 2 | 24" |
| | Uniform | 0.383 | 2 | 24" |
| 2 | Control | Graded | 2 | 24" |
| | Uniform | 0.383 | 2 | 24" |
| 3 | Control | Graded | 2 | 24" |
| | Uniform | 0.544 | 2 | 24" |
| 4 | Control | Graded | 2 | 24" |
| | Uniform | 0.544 | 2 | 24" |
| 5 | Control | Graded | 2 | 24" |
| | Uniform | 0.322 | 2 | 24" |
| 6 | Control | Graded | 2 | 24" |
| | Uniform | 0.322 | 2 | 24" |
| 7 | Control | Graded | 2 | 24" |
| | Uniform | 0.458 | 2 | 24" |
| **Part II - Study of the Effect of Filtration Rate** | | | | |
| 8 | Control | Graded | 3 | 24" |
| | Uniform | 0.458 | 1 | 24" |
| 9 | Control | Graded | 3 | 24" |
| 10 | Control | Graded | 1 | 24" |
| | Uniform | 0.458 | 3 | 24" |
| 11 | Uniform | 0.458 | 3 | 24" |
| 12 | Control | Graded | 4 | 24" |
| 13 | Uniform | 0.458 | 4 | 24" |
| 14 | Control | Graded | 5.5 | 24" |
| 15 | Uniform | 0.458 | 5.5 | 24" |
| 16 | Uniform | 0.383 | 3 | 24" |
| 17 | Uniform | 0.383 | 4 | 24" |
| **Part III - Study of Lag Period** | | | | |
| 18, 19 | Control | Graded | 1 | 24" |
| | Uniform | 0.458 | 3 | 12.5*** |
| 20, 21 | Control | Graded | 3 | 24" |
| | Uniform | 0.458 | 1 | 12.5*** |
| 22, 23 | Control | Graded | 2 | 24" |
| | Uniform | 0.458 | 2 | 19.5*** |
| 24, 25 | Control | Graded | 4 | 24" |
| 26, 27 | Uniform | 0.458 | 4 | 12"*** |
| 28** | Control | Graded | 2 | 24" |
| | Uniform | 0.458 | 2 | 24" |

**Uncoagulated raw water was tested
***Equivalent depth developed from Part 2 - See "Results & Discussion" for details

## PROCEEDINGS PAPERS

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

### VOLUME 80 (1954)

JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

SEPTEMBER: 484(ST), 485(ST), 486(ST), 487(CP)[c], 488(ST)[c], 489(HY), 490(HY), 491(HY)[c], 492(SA), 493(SA), 494(SA), 495(SA), 496(SA), 497(SA), 498(SA), 499(HW), 500(HW), 501(HW)[c], 502(WW), 503(WW), 504(WW)[c], 505(CO), 506(CO)[c], 507(CP), 508(CP), 509(CP), 510(CP), 511(CP).

OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

DECEMBER: 558(ST), 559(ST), 560(ST), 561(ST), 562(ST), 563(ST)[c], 564(HY), 565(HY), 566(HY), 567(HY), 568(HY)[c], 569(SM), 570(SM), 571(SM), 572(SM)[c], 573(SM)[c], 574(SU), 575(SU), 576(SU), 577(SU), 578(HY), 579(ST), 580(SU), 581(SU), 582(Index).

### VOLUME 81 (1955)

JANUARY: 583(ST), 584(ST), 585(ST), 586(ST), 587(ST), 588(ST), 589(ST)[c], 590(SA), 591(SA), 592(SA), 593(SA), 594(SA), 595(SA)[c], 596(HW), 597(HW), 598(HW)[c], 599(CP), 600(CP), 601(CP), 602(CP), 603(CP), 604(EM), 605(EM), 606(EM)[c], 607(EM).

FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

MARCH: 634(PO), 635(PO), 636(PO), 637(PO), 638(PO), 639(PO), 640(PO), 641(PO)[c], 642(SA), 643(SA), 644(SA), 645(SA), 646(SA), 647(SA)[c], 648(ST), 649(ST), 650(ST), 651(ST), 652(ST), 653(ST), 654(ST)[c], 655(SA), 656(SM)[c], 657(SM)[c], 658(SM)[c].

APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

JUNE: 702(HW), 703(HW), 704(HW)[c], 705(IR), 706(IR), 707(IR), 708(IR), 709(HY)[c], 710(CP), 711(CP), 712(CP), 713(CP)[c], 714(HY), 715(HY), 716(HY), 717(HY), 718(SM)[c], 719(HY)[c], 720(AT), 721(AT), 722(SU), 723(WW), 724(WW), 725(WW), 726(WW)[c], 727(WW), 728(IR), 729(IR), 730(SU)[c], 731(SU).

JULY: 732(ST), 733(ST), 734(ST), 735(ST), 736(ST), 737(PO), 738(PO), 739(PO), 740(PO), 741(PO), 742(PO), 743(HY), 744(HY), 745(HY), 746(HY), 747(HY), 748(HY)[c], 749(SA), 750(SA), 751(SA), 752(SA)[c], 753(SM), 754(SM), 755(SM), 756(SM), 757(SM), 758(CO)[c], 759(SM)[c], 760(WW)[c].

c. Discussion of several papers, grouped by Divisions.